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Need for an embodied energy measurement protocol for buildings: A review paper

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A B S T R A C T

Buildings consume a vast amount of energy during the life cycle stages of construction, use and demolition. Total life cycle energy use in a building consists of two components: embodied and operational energy. Embodied energy is expended in the processes of building material production, on-site delivery, construction, maintenance, renovation and final demolition. Operational energy is consumed in operating the buildings. Studies have revealed the growing significance of embodied energy inherent in buildings and have demonstrated its relationship to carbon emissions.

Current interpretations of embodied energy are quite unclear and vary greatly, and embodied energy databases suffer from the problems of variation and incomparability. Parameters differ and cause significant variation in reported embodied energy figures. Studies either followed the international Life Cycle Assessment (LCA) standards or did not mention compliance with any standard. Literature states that the current LCA standards fail to provide complete guidance and do not address some important issues. It also recommends developing a set of standards to streamline the embodied energy calculation process.

This paper discusses parameters causing problems in embodied energy data and identifies unresolved issues in current LCA standards. We also recommend an approach to derive guidelines that could be developed into a globally accepted protocol.

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1. Introduction

Buildings, building materials and components consume nearly 40 percent of global energy annually in their life cycle stages, such as production and procurement of building materials, construction, use and demolition [1]. The total life cycle energy of a building constitutes the embodied as well as the operational energy. Embodied energy is the total amount of energy consumed during the production, use (renovation and replacement) and demolition phase, whereas operational energy is the energy required to operate the building in processes, such as space conditioning, lighting and operating other building appliances [1,2]. Compared to embodied energy, operational energy constitutes a relatively larger proportion of a building's total life cycle energy [3]. However, recent research has emphasized the significance of embodied energy and has acknowledged its relative proportion of total energy, which is growing with the emergence of more energy efficient buildings [4,5]. Furthermore, the relative proportions of embodied and operational energy depend on factors, such as location, climate and fuel sources used [6]. Black et al. [7] have pointed out a relationship between energy use in buildings and greenhouse gas emissions, thus underscoring the environmental significance of embodied energy.

Current embodied energy (EE) data and databases exhibit inaccuracy and variability because of inconsistent methodologies that are used to determine the embodied energy of building materials [8]. This leaves the industry with published embodied energy values that are not comparable. Parameters, such as system boundaries, primary or delivered energy and feedstock energy, define the input variables that are included in embodied energy calculations. Other parameters, such as age and source of data, data representativeness (temporal, spatial and technological), and methods of measurement, affect data quality [8]. These parameters differ in current databases and influence the process of decision-making in the construction industry [8].

Global comparability and reliability are vital data qualities [9–13] for embodied energy research, in part because of the increasing significance of embodied energy in the total life cycle of a building. While a preference for low energy intensive building material could result in large savings in energy consumption in buildings [14–16], a high embodied energy material may also reduce a building's operational energy consumption. For an accurate comparison and informed decision, the embodied energy data of two materials or components should be measured on the basis of similar parameters. Furthermore, for successful implementation of environmental practices, such as eco-labeling, which informs the customers about the environmental characteristics of a product, it is vital that embodied energy data are accurate and consistent [17].

Although several methods exist to compute the energy embedded in a building or building material [2,18] these methods produce differing results. Most current databases of embodied energy include data that are derived using guidelines set forth by the International Standardization Organization (ISO) for Life Cycle Assessment (LCA). Most research studies performed either energy analysis or LCA to calculate embodied and operational energy in the whole life cycle of a building. Studies [11,19,20] that performed LCA mention either using ISO LCA standards or none. However, studies [21–23] that are skeptical about using LCA for assessing buildings in environmental impact terms exist. Literature suggests that development of a set of standards or protocol could minimize problems of variation in energy data and could introduce accuracy and completeness to the embodied energy figures. ISO LCA standards do not provide complete guidance to the process of LCA. Moreover, some issues, such as system boundary definition and data quality, remain unresolved [24,25].

This paper performs a review of literature in the realm of embodied energy and Life Cycle Assessment (LCA) and provides a survey of existing international LCA standards. We identify parameters causing variations in embodied energy data, and determine unresolved issues in existing international LCA standards. Furthermore, we also recommend an approach to establish an embodied energy measurement protocol. Both the LCA and embodied energy analysis literature are utilized, as nearly all of the LCA studies cited in this paper actually involve embodied energy analysis.

2. Embodied energy: definition and interpretation

Buildings are constructed with a variety of building materials, each of which consumes energy throughout its stages of manufacture, use, deconstruction and disposal. Similarly, each building consumes energy during its life cycle in stages, such as raw material extraction, transport, manufacture, assembly, installation as well as its disassembly, demolition and disposal. Energy is expended in various construction processes of a building during the pre-construction phase. Post construction phases, such as renovation and refurbishment, and final demolition and disposal also consume energy. The energy consumed in these life cycle stages of a building is collectively interpreted as embodied energy. According

to Miller [26], the term "embodied energy" is subject to numerous interpretations rendered by different authors and its published measurements are found to be quite unclear.

Hegner [3] presented an interesting explanation of embodied energy, citing Kasser and Poll, according to whom, only energy that is available in a limited amount should be considered embodied energy. Here, the author relates the phenomenon of embodied energy to greenhouse gas emissions, as a major fraction of primary energy that is available in a limited amount comes from fossil fuel. Furthermore, it is stated [3] that research studies provide their own definitions, which differ from other comparable studies. Much like Hegner [3], Upton et al. [27] defined embodied energy as total embodied energy minus the renewable fraction of total energy. Are these studies indicating that only non-renewable energy needs to be accounted for in the embodied energy calculation? Clearly, embodied energy definitions represent differences of opinion about the system boundaries to be adopted and type of energy to be included in embodied energy analyses [3,22].

2.1. Embodied energy model for a building

The total life cycle energy of a building includes both embodied and operational energy [1,2]:

(1) *Embodied energy (EE):* Energy sequestered in buildings and building materials during all processes of production, on-site construction, and final demolition and disposal. Overall, embodied energy in a building has two primary components, direct energy and indirect energy [8]:

   Direct energy: Energy consumed in onsite and offsite operations, such as construction, prefabrication, assembly, transportation and administration (see Fig. 1) [8].

   Indirect energy: Energy consumed in manufacturing the building materials, in renovation, refurbishment and demolition processes of the buildings. This includes *initial embodied energy*, *recurrent embodied energy* and *demolition energy*. Initial embodied energy is consumed during the production of materials and components and includes raw material procurement, building material manufacturing and finished product delivery (transportation) to the construction site. Recurrent embodied energy is used in various maintenance and refurbishment processes during the useful life of a building. Demolition energy is expended in the processes of a building's deconstruction and disposal of building materials (see Fig. 1) [8].

(2) *Operational energy (OE):* Energy expended in maintaining the inside environment through processes such as heating and cooling, lighting and operating building appliances. The focus of this paper is not on operational energy (see Fig. 1).

3. Significance of embodied energy

Until recently, the emphasis of energy conservation research was on the operational energy of a building, while embodied energy was assumed to be relatively insignificant. However, current research has invalidated this assumption and found that embodied energy accounts for a significant proportion of total life cycle energy [2]. Operational energy conservation may be accomplished with readily available energy efficient appliances, advanced insulating materials and the equipment of building performance optimization [1,4,28]. For example, an increase in the number of Energy Star labeled home appliances in the United States could reduce operational energy gradually [29] (see Fig. 2). Embodied energy, however, can only be reduced if low energy intensive materials and products are selected at the initial stages of building design.

As buildings become more energy efficient over time, the relative proportion of embodied energy in the total life cycle energy increases [2,4–6,19,30]. Sartori and Hestnes [28] concluded, after reviewing 60 case studies from past literature, that for a conventional building, the embodied energy could account for 2–38 percent of the total life cycle energy, whereas, for a low energy building, this range could be 9–46 percent. Thormark [31] asserted that embodied energy of a low energy house could be equal to 40–60 percent of total life cycle energy.

Recently, Huberman and Pearlmutter [20] determined that the embodied energy in a climatically responsive building in Negev desert region in Israel is 60 percent of total life cycle energy (50 year service life). However, Plank [4] concluded that in the United Kingdom, a heating dominated region, the embodied energy accounts for only 10 percent of the total life cycle energy. Nebel et al. [6] explained that the proportion of embodied energy in total life cycle energy depends on geographic location and climate. In heating dominated regions, embodied energy represents a relatively low percentage of total life cycle energy, which may not be true for a moderate or cooling dominated region due to the latter's relatively lower operational energy [6]. Little agreement exists on the importance and relative proportion of embodied energy in total life cycle energy of a building [5].

Gonzalez and Navarro [32] asserted that building materials possessing high-embodied energy could result in more carbon dioxide emissions than would materials with low embodied energy. Hegner [3] and Black et al. [7] explained embodied energy as a sum of energy types that are available in limited amounts (non-renewable). Other authors [3,7,33] indicated that energy consumption in buildings directly relates to greenhouse gas emissions and eventually, global warming. Studies such as Black et al. [7] discussed the close relationship of environmental impacts to the energy consumption in buildings. Recent studies on embodied energy calculations, such as [34], already started distinguishing the non-renewable fraction of the total energy in building so as to indicate the greenhouse gas emission potential. Black et al. [7] cited energy use tables (2006) provided by Natural Resources Canada, according to which building sector contributes 29 percent of total secondary energy use and nearly 27 percent of total greenhouse gas emissions in Canada.

4. Current embodied energy calculation methods

Among primary embodied energy determination methods are statistical analysis, process-based analysis, economic input/output-based analysis and hybrid analysis. These methods differ in their collection of data about energy inputs in the main (e.g. material production) and support processes (e.g. administration) [1,8,23,33,35–38]. Each of these currently used methods possesses advantages as well as disadvantages, which are discussed in [8] and also in later sections of this paper. Refs. [38,39] used these methods to calculate embodied energy in buildings and building materials. Incompleteness and inaccuracy are two key issues associated with these methods, which may cause variation in embodied energy values [35,36].

Assessment of total energy in buildings should be performed keeping a life cycle perspective, which may include energy and material inputs during all life cycle stages [4,23,36,40]. Furthermore, there is a growing interest in adopting a life cycle approach in current research in this area. Research studies have used Life Cycle Assessment to calculate embodied energy in buildings, building materials and assemblies. In fact, current embodied energy calculation methods exist in LCA models. LCA is an effective tool for measuring embodied energy in buildings; however, it is data intensive and requires robust data [40]. Embodied energy

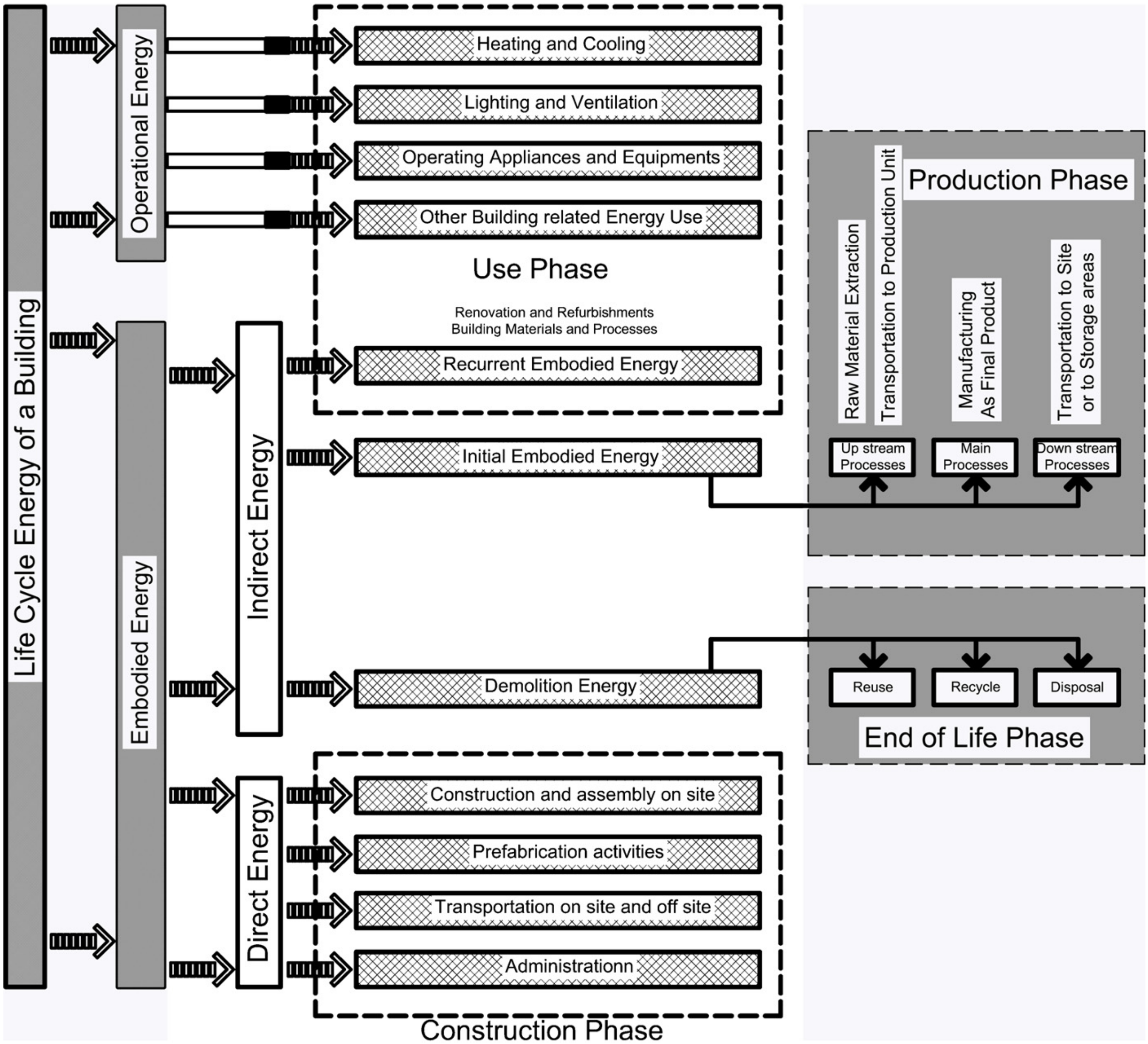

Fig. 1. Embodied energy model for the life cycle of a building (based on [11]).

calculation is one of many components (e.g., other life cycle energy use, greenhouse gas emissions, global warming potential, toxicity, etc.) of the process of LCA of a material or a product [18]. Lawson [18] informed that the LCA can be used for measuring energy consumption and energy usage in a material's useful life. Lenzen et al. [41] commented on the relationship of embodied energy and LCA, stating that the "entire philosophy of Life Cycle Assessment builds on the notion that energy (and other sources and pollutants) is passed on by being embodied in the intermediate products and materials that are then passed on between producers, until that reach the final consumers." Embodied energy in the context of LCA could represent energy consumption, greenhouse gas emissions and depletion of nonrenewable fossil fuel sources. A variety of LCA tools in the form of software exist, along with datasets of environmental impacts of building materials. These tools, such as ATHENA, BEES 4.0, Ecoinvent, Eco-Quantum, Envest 2, OPTIMIZE, LICHEE, SimaPro, etc. provide a user-friendly approach to determine life cycle impacts of a building [23,36]. However, most of these do not cover all stages of a building's life cycle. Furthermore, none of the existing tools and datasets possesses the capability to perform a full Life Cycle Assessment of a building [23,36].

Most embodied energy calculations performed as a part of LCA by past research studies followed LCA ISO standards (2006). Research studies that focus solely on embodied energy measurement either did not mention whether or not they followed any standards, or followed ISO standards (see Table 1). Most current databases of embodied energy include data that are derived using guidelines set forth by the International Standardization Organization (ISO) for Life Cycle Assessment (LCA). Hammond and Jones, under the Carbon Vision Buildings Program at the University of Bath, England, are establishing one large and comprehensive database of energy and carbon embodied in building materials [42]. One criterion for selecting energy data used by this study includes data that comply with ISO standards [33]. Crawford [43] performed the embodied energy assessment using process analysis based on the ISO 14040 standards. Huberman and Pearlmutter

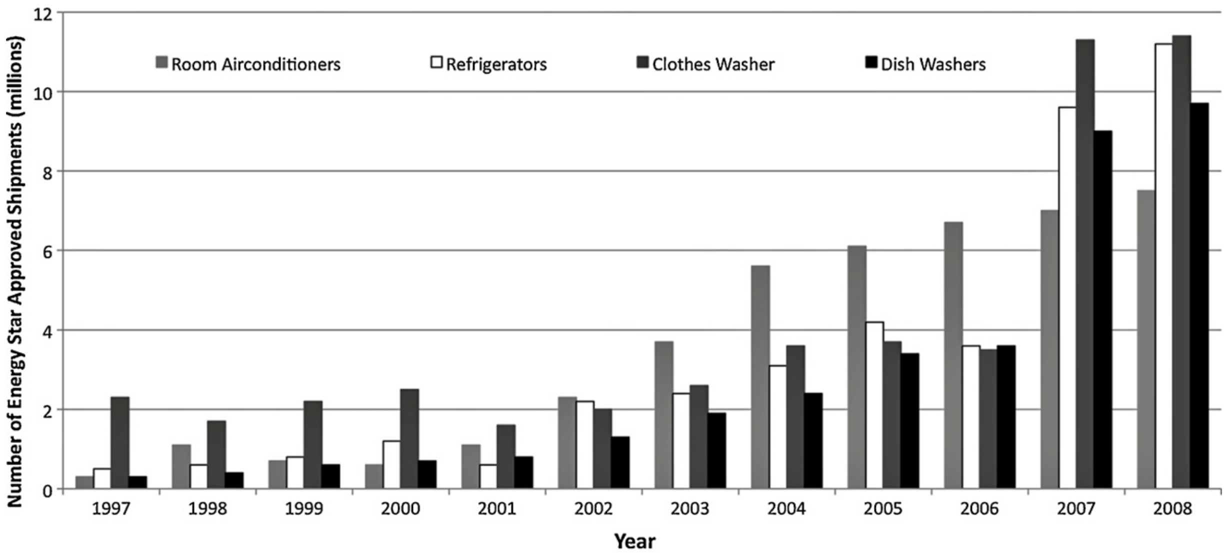

Fig. 2. Growing number of Energy Star approved building appliances (based on [48]).

[20] and John et al. [34] referred to ISO 14040 standards while conducting life cycle energy analyses (that include embodied energy). Table 1 presents a list of research studies, along with their selected types of data analysis and the standards they followed.

The processes of both LCA and embodied energy analysis are discussed in this manuscript, as all referred LCA studies involve embodied energy calculations. Literature related to both processes is referred to and cited in the paper.

4.1. Literature opinion on LCA use in buildings

LCA, which was originally designed to evaluate a manufactured product's life cycle in terms of its environmental impacts, cannot be directly applied to buildings. Using LCA to assess the impacts of a life cycle is not straightforward due to multiple reasons [21–23]. Buildings are large in size, complex and unique in nature and their construction often involves the assembly of a range of manufactured materials and products. These materials, products and construction processes may hold a variety of environmental impacts that are difficult to track. Buildings possess a much greater life span than most other products; tracking and assessing such a long span requires considerable effort in terms of data collection and interpretation. Furthermore, buildings are dynamic in nature and undergo changes, such as alteration, extension and renovation, and include activities, such as maintenance and replacements that further complicate the process of collecting relevant information [21,23]. Unlike other manufactured products, building production processes are less standardized, making data collection a difficult task. To further complicate the matter, a building's delivery process involves a number of key players having different motivations [21,23]. The lack of reliable and accurate information and the limited information about energy and environmental impacts of building materials and components hamper the LCA process for a building [21].

5. Problem of variations in embodied energy data

Previous studies of embodied energy analysis and computation exhibit considerable variation in embodied energy results owing to numerous factors [1,2,4,5,8,11,30,55–58]. Dixit et al. [8] calculated a standard deviation of 1.56 GJ/m^2 and 5.4 GJ/m^2 in embodied energy values of residential and commercial buildings, respectively, as reported by studies cited in Ding [1]. Worth [59], Pears [10] and Pullen [11] warned that the databases evolved to this point

Table 1
A sample of literature available on embodied energy calculation.

Research study	Location	Analysis/tool	Standard	EE	CE
Pullen (1996) [11]	Australia	EA/Self-derived Spreadsheet method	Not described	√	√
Adalberth (1997) [44]	Sweden	LCA/Self-derived LCA method	Not described	√	X
Pullen (2000) [38]	Australia	EA/Economic I/O data	Not described	√	X
Thormark (2002) [45]	Sweden	EA/Analysis using published data	Not described	√	√
Scheuer et al. (2003) [46]	USA	LCA/DEAM software	SETAC, ISO 14041	√	√
Guggemos and Horvath (2005) [47]	USA	LCA/LCA model using process and economic I/O data	Not described	√	√
Norman et al. (2006) [48]	Canada	LCA/LCA model using economic I/O data	Not described	√	√
Junnila et al. (2006) [49]	Finland	LCA/LCA model using process and economic I/O data	ISO 14040	√	√
Pearlmutter et al. (2007) [50]	Israel	LCA/LCA model using Process and published data	ISO 14040 and 14044	√	X
Langston and Langston (2007) [39]	Australia	LCA/LCA model using economic I/O-based hybrid data	Not described	√	X
Citherlet and Defaux (2007) [51]	Switzerland	LCA/LCA model using ESU database, Zurich	Space heating EN ISO 13790	√	√
Huberman and Pearlmutter (2008) [20]	Israel	LCEA/LCA model using Process and published data	ISO 14040 and 14044	√	√
John et al. (2008) [34]	New Zealand	LCA/GABI software data and published data	ISO 14040 and 14044	√	√
Sobatka and Rolak (2009) [52]	Poland	LCA/LCA model using published data	ISO 14040/42	√	√
Gustavsson and Joelsson (2010) [19]	Sweden	LCA/LCA model using Process and published data	Not described	√	√
Verbeeck and Hens (2010) [53]	Belgium	LCA/Ecoinvent database	Not described	√	X
Blengini and Decarlo (2010) [54]	Italy	LCA/LCA model using published data	ISO 14040 and 14044	√	√

EA, energy analysis; EE, embodied energy; CE, carbon emission; LCA, Life Cycle Assessment; LCEA, life cycle energy analysis.
Note: Shaded cells indicate studies published after the 2006 update in ISO LCA standards.

are inconsistent and show significant variability. Past and present research has pointed out errors and variations in embodied energy figures. Pears [10] asserted that the different information sources and inclusion of either primary or secondary energy could result in 30 to 40 percent variation in reported embodied energy. Lenzen [37] warned of a possible truncation error in the conventional process analysis, which could be as great as 50 percent, depending upon the product and its manufacturing process under consideration. In fact, the incompleteness in conventional process-based analysis could be as large as 20 percent [60]. Pullen [61] noted that process analysis does not include upstream processes (raw materials extraction and transportation) and some downstream processes (transporting finished products to construction sites) and, thus, its results are inconsistent. Datasets that exhibit variability cannot be compared and the goals of environmental labeling and low embodied energy material preference cannot be reached [1,11,26,37,57,59]. Worth [59] asserted that current data with these problems cannot contribute fully to energy conservation practices.

5.1. Impact of embodied energy variation on current environmental practices

5.1.1. Eco-labeling

Eco-labeling of products includes informing consumers about the environmental characteristics of a product and it has been adopted as an important tool to evaluate products in environmental quality terms [13,17,62]. Energy consumption (embodied energy in products) and energy conservation are the environmental characteristics included in eco-labeling schemes [62,63]. The United Kingdom Eco-labeling Board has indicated grave concerns for embodied energy in building materials and material use in the construction industry [64]. Analytically, LCA takes into account the whole life cycle impact of the product; hence, it provides necessary support to environmental assessment tools, such as eco-labeling [63].

The embodied energy of a product is a useful criterion for judging environmental performance [17]. Johnston et al. [9] warned that if eco-labels did not provide correct and relevant information, the decision-making and product preference would be relatively weak.

5.1.2. Environmental preference of materials or products

Environmental selection of materials or products could result in greater energy use savings and an eventual decrease in CO_2 emissions due to energy production [14]. Atkinson [14] found that the energy savings, due to environmental preference, could be as large as 20 percent, while Thormork [15] determined a reduction of 17 percent and an increase of 6 percent in embodied energy values due to the right or wrong selection of materials, respectively. It is important to identify low embodied energy materials or products in order to enable building professionals, who are involved in decision-making, to make environmentally benign choices [13].

Unfortunately, industry lacks reliable information about the amount of energy embodied in a material or product that could be used for the purpose of environmental preference [13]. Consequently, uncertain information about embodied energy is available to people involved in decision-making and their decisions are influenced by this uncertainty [10]. Differing energy values hamper the process of selecting environmentally friendly materials that may involve comparing two products' energy intensity terms [10,16,59]. Such comparisons, if performed, are not valid, as they are based on differing energy data [11,14].

5.1.3. Green building rating systems

Embodied energy in buildings and their constituent materials and components can be used as an important criterion in green building assessment systems [65]. Green building assessment systems e.g. BREEAM, HK-BEAM, BEPAC, HQE, VERDE, and GBTOOL, include the issue of embodied energy clearly in their green building evaluation criteria [66]. In particular, Green Globe and LEED, through evaluation criteria like reduction in material consumption and use of locally available materials, acknowledge the importance of embodied energy in the green building assessment process [66].

The calibration of embodied energy contents is complex and as a result, it is often not performed [67]. Unavailability of accurate data and lack of appropriate tools limit the potential of embodied energy to be a vital criterion in environmental assessment of buildings [65,67].

6. Research needs suggested by relevant literature

A review of past and recent literature on LCA and embodied energy research is presented below. Three recommendations are identified in this review of literature that point out a necessity to derive and follow a set of standards or a protocol while performing an embodied energy measurement (see Table 2).

6.1. Missing a robust database of embodied energy

Crawford [43] and Peereboom et al. [68] suggested that necessary information for decision-making is either not available or is available in an unusable form. Furthermore, the authors conclude that "unreliable and incomplete data" about the energy contents of building materials and assemblies often hamper the process of decision-making. In order to realize greater environmental benefits, development and availability of a robust (relatively accurate and complete) and reliable embodied energy database (that assures data quality and representativeness) is essential [6,11,13,24,33,36,43,68]. Pears [10] and Raynolds et al. [12] argued that creation of such a database is possible only if validation, standardization and comparability are introduced in current research efforts. Material selectors would be in a better position to evaluate and prefer a particular material if a sound database of magnitude of energy consumption as well as greenhouse gas emission were made available to them [59].

6.2. Lack of standard methodology for embodied energy calculation

The field of embodied energy research lacks a standard methodology to accurately and completely determine energy embodied in a building [5,23,35,36,72]. Existing methods are either incomplete or inaccurate, and hence, they produce differing results. According to Ting [36], a significant improvement is urgent in order to develop a standardized approach to measure the energy embodied in a building. Frey [5] asserted that embodied energy research is "plagued with methodological issues" and lacks "scientifically agreed upon" standards and methodology. Moreover, the author points to uncertainty in data collection and undefined system boundaries.

6.3. Need to develop a protocol for embodied energy measurement

Pullen [11] warned that the development of a sound embodied energy method requires addressing the problems associated with data quality. Studies, such as Pears [10], Pullen [11], and Lippiatt and Norris [69], previously emphasized the derivation of a set of guidelines to address these problems and to make the selection of less energy intensive materials easier for building practitioners.

Recently, a National Institute of Standards and Technology technical note [76] referred to the missing embodied energy standards

Table 2
Sources presenting critical review of ISO LCA standards and respective recommendations.

Research studies	Critical review of current LCA standards	Recommendations		
		Need to develop a protocol	Need to establish a robust database	There is no standard or correct method for EE calculation
Worth (1993) [59]			√	
Lippiatt and Norris (1995) [69]		√		
Pears (1996) [10]		√	√	√
Pullen, 1996[11]		√	√	√
Lawson (1996) [18]				√
Peereboom et al. (1998) [68]			√	
Crowther (1999) [2]				√
Raynolds et al. (2000) [12]	√		√	
Davies (2001) [16]			√	
Suh et al. (2004) [70]	√			
ICANZ (2006) [71]		√		
John-Fernandez (2006) [13]			√	
Ting (2006) [36]			√	√
Menzies et al. (2007) [72]		√		√
Hammond and Jones (2008) [73]	√		√	
Reap et al. (2008) [24]	√		√	
Weidema et al. (2008) [74]	√			
Zamagni et al. (2008) [25]	√			
Frey (2008) [5]		√		√
Langston and Langston (2008) [35]			√	√
AWC (2009) [75]		√		
Crawford (2009) [43]			√	
Khasreen et al. (2009) [23]		√	√	√
Ramesh et al. (2010) [21]			√	
Hammond and Jones (2010) [33]			√	
NIST (2010) [76]		√		

Note: Shaded cells indicate studies published after the 2006 update in ISO LCA standards.

as a barrier to sustainability and set it forth as a priority. Menzies et al. [72] argued that, in spite of the number of efforts to conduct LCA and establish inventories, no global protocol has been developed that could treat problems in LCA or embodied energy results. The Insulation Council of Australia and New Zealand [71] media release commented that there exists no international protocol for measuring embodied energy in building materials. A demand for a national set of standards for measuring embodied energy is also observed by studies such as [13], as existing international standards may not be suitable for differing local conditions. Fernandez [13] also suggested developing embodied energy standards at the regional level in order to consider and address climatic differences at the national level.

The Federal Stimulus Package for energy efficiency and energy conservation project in the United States requires construction and major renovation projects to perform LCA and embodied energy calculations for building materials used (Bill, SB 5385). Moreover, SB 5385 requires the Department of General Administration to evolve guidelines for the establishment of a method for embodied energy calculation in building materials. The bill also seeks the use of low embodied energy building materials in construction and major renovation projects that receive funds from the stimulus package [75].

7. How to standardize the embodied energy measurement process?

Dixit et al. [8] identified parameters that not only define embodied energy but also govern the quality of embodied energy data. Moreover, if these parameters are deferred among embodied energy calculations, a variation is observed in the end results. Literature, as discussed earlier, reflects the need for a standard protocol that streamlines the process of embodied energy measurement. Any such effort would remain incomplete without a literature survey of existing standards, as it would be important to know whether or not these standards are successful in streamlining the LCA process. Sections 7.1 and 7.2 describe in detail the parameters causing variation in embodied energy results and a literature survey of currently used standards.

7.1. Parameters responsible for variation in EE data

The review of relevant literature reveals ten parameters that are responsible for affecting the quality of embodied energy results adversely [8]. These parameters are presented in the form of a matrix, along with the research studies supporting them, elsewhere [8] as well as in this paper (see Table 3). Table 3 provides an updated list of literature sources that discuss these parameters, and the following sections describe the parameters.

7.1.1. System boundaries

The system boundary defines the number of energy and material inputs that are considered in the embodied energy calculation. Stages, such as raw material extraction in distant upstream, and demolition and disposal in farthest downstream, should be included in system boundaries. Research studies have adopted different system boundaries and, as a result, their measurement figures vary and cannot be compared with each other [1,5,23,24,26,33,37,43,57,78] (see Fig. 3).

7.1.2. Methods of embodied energy measurement

Process analysis, statistical analysis, input output analysis and hybrid analysis are among the major methods used for embodied energy computation [1,4,23,30,61]. These methods possess different limitations and their level of accuracy varies. As a result, their embodied energy results differ [4,23,26,30,56–58,61]. Process analysis is accurate, as it takes into account energy and material input in each process. This, however, becomes difficult, as some upstream

Table 3
Matrix of parameters causing variation embodied energy, and their sources (updated from Dixit et al. [11]).

Authors and year of study/research	Parameters									
	System boundaries	Method of EE analysis	Geographic location	Primary and delivered energy	Age of data	Data source	Data completeness	Manufacturing technology	Feedstock energy consideration	Temporal representation
Pears (1996) [10]		√		√		√		√		
Pullen (1996) [11]		√	√			√	√			
Peereboom et al. (1998) [68]			√		√	√		√		√
Pullen (2000) [38]				√						
Pullen (2000) [61]		√	√		√			√	√	
Miller (2001) [26]	√	√								
Ding (2004) [1]	√		√		√	√				
Horvath (2004) [57]	√	√								
Crawford and Treloar (2005) [56]	√	√								
ISO 14040 (2006) [77]	√		√		√		√	√	√	√
Lenzen (2006) [37]	√		√		√			√		√
Junnila et al. (2006) [49]		√	√		√			√		
Ting (2006) [36]			√					√		
Menzies et al. (2007) [72]			√		√	√	√	√		
Sartori and Hestnes (2007) [28]			√	√		√			√	
Nebel and Gifford (2007) [22]			√			√	√	√		√
Ding (2007) [78]	√	√						√		
Hammonds and Jones (2008) [73]	√	√	√		√					
Reap et al. (2008) [24]			√		√			√		√
Plank (2008) [4]		√				√				
Frey (2008) [5]	√				√					
Khasreen et al. (2009) [23]	√	√	√			√	√	√		√
Crawford (2009) [43]	√	√								
Hammond and Jones (2010) [33]	√			√				√	√	
Optis and Wild (2010) [30]	√	√	√			√		√		√
Joseph and Tretsiakova-McNally (2010) [58]		√	√					√		

Note: Shaded cells indicate studies published after the 2006 update in ISO LCA standards.

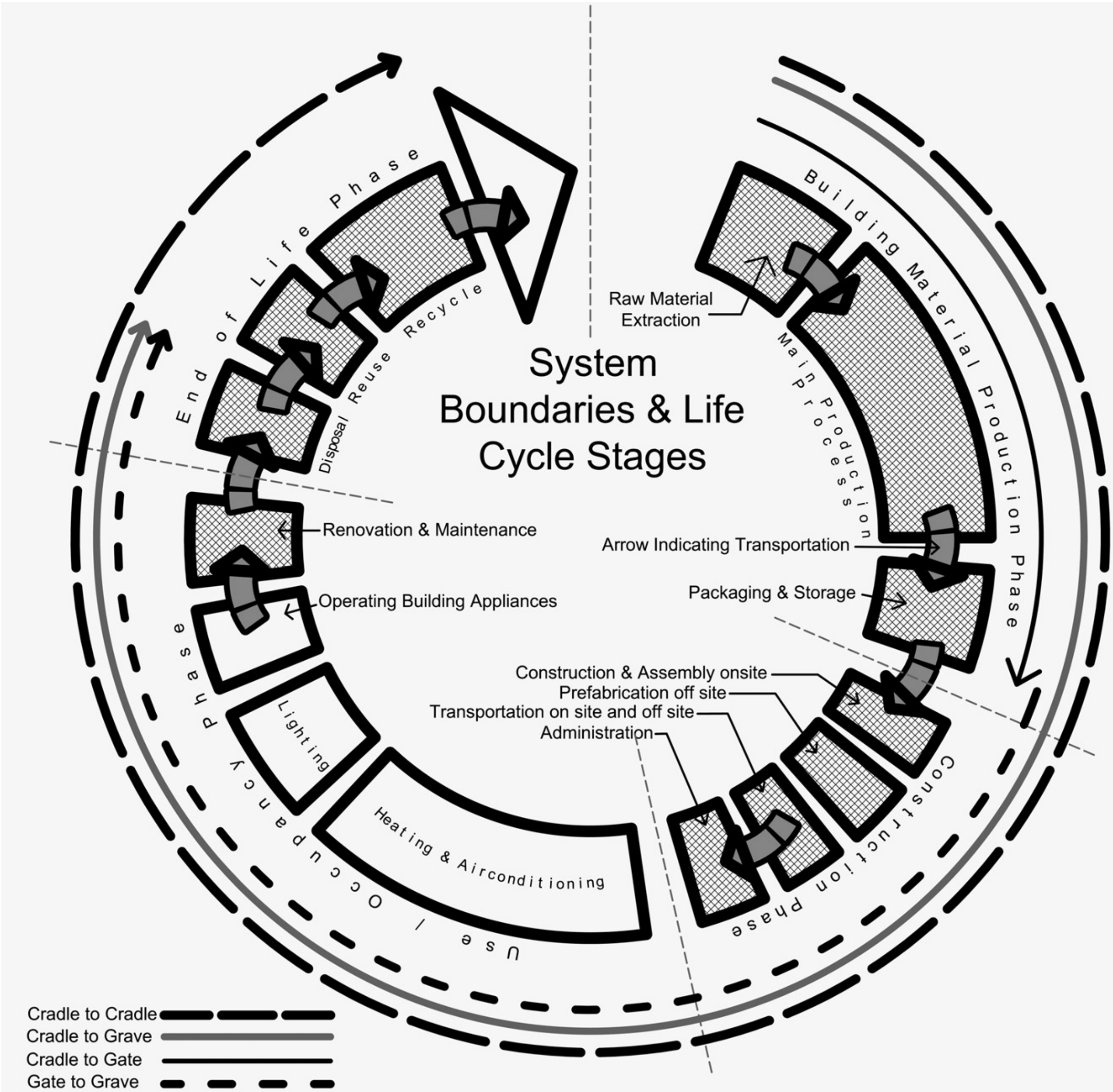

Fig. 3. System boundaries and life cycle stages of a building.

and downstream processes could not be tracked accurately. Thus, process analysis suffers from incompleteness [23,36,43,50]. Input output analysis is complete, as it is based on economic input output data for the entire construction sector; however, such analysis involves data aggregation that makes its results relatively inaccurate [23,36,43,50].

7.1.3. Geographic location of the study

Research studies performed in different countries differ from one another in terms of data relating to raw material quality, production processes, economy, delivered energy generation, transportation distances, energy use (fuel) in transport, and human labor. This eventually affects the determination of energy consumption and their results vary significantly [1,10,11,18,23,28,30,37,58]. Processes of industrial and economic sectors differ greatly and thus influence the calculated embodied energy values. Different locations of data could affect the embodied energy results because of variations in production processes and energy tariffs [61].

7.1.4. Primary and delivered energy

Primary energy is defined as “the energy required from nature (for example, coal) embodied in the energy consumed by purchaser (for example, electricity)” and delivered energy is defined as “the energy used by the consumer” [8]. The measurements of embodied energy are consistent if they are based on primary energy [8], but if delivered energy is considered, the results could be misleading and ambiguous [8,28]. Furthermore, both operational and embodied energy must be measured in terms of primary energy consumption in order to attain consistency and to acquire the most appropriate environmental implications, such as greenhouse gas emissions [8,19].

7.1.5. Age of data sources

Research studies based on old and current data sources could differ significantly as a result of the changing technology of manufacturing and transportation. Consideration of old transportation energy data could affect energy values, as new vehicles have more fuel efficiency and a different fuel structure. Any study based on such conflicting data sources could be misleading and uncertain and the end results could vary considerably [5,24,49,68]. Building material performance and material production efficiency would be enhanced over time and could be responsible for variations in measurement figures [61]. Hammonds and Jones [73] attempted to consider current data sources in establishing the inventory of carbon and energy because of their relevance, certainty and temporal representativeness.

7.1.6. Source of data

Research studies use data that are collected using different approaches. Some studies derive their own data by calculating the energy intensiveness, while others utilize energy figures calculated by other studies. This subjective selection of data influences the final results significantly [1,4,23,30]. Peereboom et al. [68] suggested that practitioners of Life Cycle Analysis (LCA) rely on various sources of information and do not have access to primary data, which leads to uncertainty and variability in LCA results. Data source is an important parameter, and its reliability, certainty, and transparency must be considered when performing LCA [37].

7.1.7. Data completeness

According to Menzies et al. [72] and Peereboom et al. [68], research studies often do not have access to primary data sources and rely on secondary data sources that may or may not be complete. This incompleteness is due to either the limitations of the calculation method or subjective selection of system boundaries. Menzies et al. [72] asserted that the accessibility of data, methodology adopted, and selection of system boundaries govern data completeness, which could affect the reliability of end results significantly. Data completeness must be considered while choosing one material dataset over another [22,23].

7.1.8. Technology of manufacturing processes

Differing technologies of material manufacturing possess varied levels of energy consumption, as advanced technology could consume less energy due to energy efficient processes. In the similar geographic location and during the same time period, two studies could generate different results if they are extracting information from two material manufacturers using different technologies [8,10]. Technological representativeness is an important quality of data that should be taken into account in order to eliminate inconsistency and variability of results [23,24,30,37,68,72].

7.1.9. Feedstock energy consideration

Feedstock energy is the energy embedded in the ingredients used in the process of manufacturing a material. Petrochemicals, such as oil and gas, are used as a material input in the manufacturing process of products, e.g. plastics and rubber [8]. Feedstock energy needs to be considered in the calculation of the total embodied energy in a material [73]. Inclusion of feedstock energy in embodied energy calculation or LCA could cause variations in embodied energy figures, and such figures are not comparable across research studies [61].

7.1.10. Temporal representativeness

A significant data quality indicator in embodied energy analysis and LCA is temporal representation [23,24,30,68]. Some energy studies are based on recently developed technology, and some studies consider a mix of new and old technology [79]. The end results of such studies differ and are not consistent.

This list of parameters is not exhaustive and may include more factors that are responsible for variations. Peereboom et al. [68] did not rule out the possibility of existence of other parameters.

7.2. Survey of current standards used for embodied energy measurement

Studies that involved the calculation of embodied energy in building and building materials either did not mention using any standard or used standards provided by ISO and the Society for Environmental Toxicology and Chemistry. ISO and SETAC are the two key organizations that are working towards standardization and scientific development of LCA [80]. In 2006, ISO reviewed and updated its existing suite of standards for conducting LCA. In spite of the existence of ISO LCA standards, current literature (before and after 2006) emphasizes the need to establish a robust database of embodied energy of building products using a separate embodied energy standard. Research studies from 1993 [59] through 2010 [33] have been indicating an urgency to address the issue of a lack of consistent and accurate embodied energy data. It would be vital to survey currently used standards and to seek the opinion of literature about their performance in streamlining and standardizing the process of LCA.

7.2.1. ISO – International Standardization Organization

The ISO is a global federation of national standards bodies or ISO member bodies that works toward the preparation of international standards. ISO released a second edition of ISO 14040, along with ISO 14044, in 2006, to replace earlier versions, such as ISO 14040: 1997, ISO 14041: 1998, ISO 14042: 2000 and ISO 14043: 2000 [77,81].

1. ISO 14040-2006: Environmental Management – Life Cycle Assessment – Principles and Framework [77]

   The ISO 14040 standards for LCA define the various terms used in LCA practice and provide a general description of LCA. Furthermore, it outlines the methodological framework to execute all four steps of a typical LCA: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and life cycle interpretation.
2. ISO 14044-2006: Environmental Management – Life Cycle Assessment – Requirements and Guidelines [81]

   The ISO 14044 standards list the requirements and guidelines in detail and address issues related to allocation and system boundaries. The standards describe data and data sources, and state data quality requirements (in the form of data quality indicators) to ensure higher quality data. Moreover, explanation is also given for the treatment of missing data or data gaps in the LCA database.

7.2.2. SETAC – Society for Environmental Toxicology and Chemistry

The Society for Environmental Toxicology and Chemistry has had greater influence on the development of LCA for a long time. SETAC has established groups to address the problems and issues related to data quality. A working group called “Data availability and data quality” was formed in April 1998 to improve the quality of LCA data. Fava [80] noted that SETAC has been heavily involved in the development of LCA terminology and technical framework. Furthermore, SETAC has collaborated with the United Nation’s Environmental Program (UNEP) to form a group called UNEP/SETAC Life Cycle Initiative that is dedicated to evolving tools for evaluating various products.

1. SETAC: Guidelines for Life Cycle Assessment – a code of practice

This document provides direction to LCA methodology by describing the general principles and framework to execute, review, present and use the results of LCA. The framework, as suggested by SETAC, incorporates four phases of LCA, such as goal definition and scoping, inventory analysis, impact assessment and improvement assessment. Finally, an analysis and interpretation of the results is discussed. Topics, e.g. data quality, LCA applications and limitations, are stated and discussed in later sections.

7.3. *Critical review of current standards: contentious issues*

The incompleteness and uncertainty of available data and the lack of standard and comparable methodology adversely affect the process of decision-making [69]. Fava [80] claimed that the ISO 14000 family has evolved and set up the rules and guidelines for conducting LCA worldwide in a consistent and reproducible manner. Weidema et al. [74] argued that, despite the currently available standards for LCA, along with product declaration and greenhouse gas accounting, individual efforts to create methodology and guidelines still exist. Among the major efforts is the UK Carbon Footprint Label as a Public Available Standard (PAS) that is being developed at the request of the Carbon Trust and British Department of Environment, Food and Rural Affairs (DEFRA). British Standards (BS) aimed to develop a set of standards that are rigorous but easily applicable [74]. However, Weidema et al. [74] questioned, “Do we need additional standards?” and state, “The existing ISO standards are vague on several crucial points.”

In spite of so much standardization effort, the LCA process still needs more clarification and improvement. Hammond and Jones [73] claimed that it would be ideal to comply with ISO standards; however, studies that follow ISO standards still reflect significant differences in the end results. Lu et al. [82] warned that simply complying with ISO LCA standards would not guarantee a high quality LCA, as some issues in these standards need clarification. Heijungs et al. [83] pointed out the factual errors in ISO LCA standards, such as mentioning total Global Warming Potential (GWP) of carbon dioxide as 2750 kg instead of 1 kg. Research studies, such as Weidema et al. [74], Jeswani et al. [84], Heijungs et al. [83], Zamagni et al. [25], Reap et al. [24], Suh et al. [70], and Raynolds et al. [12] pointed out the problems associated with the issues of system boundaries and allocation in current ISO standards for LCA. Referring to literature regarding critical reviews of SETAC and ISO standards identifies the following issues.

7.3.1. *System boundaries*

There is a lack of clarity, subjectivity and an issue of truncation error in the current system boundary selection criteria and procedures mentioned by LCA standards [12,24,25,70,74,83,84]. Weidema et al. [74] referred to system boundary and co-product allocation in ISO standards when they state that the “ISO 14044 LCA standard is unnecessarily open for misinterpretation.” Furthermore, the cutoff rules for system boundaries are presented in an ambiguous and complicated manner [25,74,83]. For example, ISO 14040 standards recommend including all processes, directly or indirectly related to a product’s main manufacturing process; however, later it states that the processes with no significant influence on the end results could be excluded [25]. Moreover, Suh et al. [70], Raynolds et al. [12] and Zamagni et al. [25] noticed that the ISO standards mention unit process inclusion in the assessment in terms of percentages (e.g. 90 percent of mass flow or 99 percent of total energy demand), but the problem is practitioners never know when these limits are reached because they are not aware of all the data for the entire system. This makes it impossible to comply with the system boundary selection method for ISO standards. Suh et al. [70] and Raynolds et al. [12] claimed that it is impossible to select a system boundary that truly complies with ISO standards. Raynolds et al. [12] stated, “The ISO method of system boundary selection is rigorous and robust in theory, but in practice fails.”

7.3.2. *Allocation*

It is still unclear which approach must be adopted for the purpose of allocation as there is disagreement regarding current approaches. The feasibility of the current method of allocation is questionable according to critiques [12,23,25,70,74,84]. Zamagni et al. [25] argued that the ISO procedures for allocation in LCA are prone to conflicting interpretations and researchers at times do not agree with these procedures. Reap et al. [24] asserted that the manner in which ISO standards deal with system boundaries and allocation issues in LCA introduces subjectivity and truncation error into the assessment. Zamagni et al. [25] stated that the ISO permits selection of any LCA method and adds subjectivity to it.

7.3.3. *Methodology for calculation*

Heijungs et al. [83] observe that existing ISO LCA standards for performing LCA calculations provide no mathematical model, formula or expression. The ISO framework lacks clear procedural guidance during the interpretation phase of LCA. “The methodological framework as in ISO standard is often judged too narrow for the application needed,” Zamagni et al. [25] added. Furthermore, the ISO standards for LCA mention a framework for the LCA steps but fail to provide sound methodology to execute these steps. Furthermore, Suh et al. [70] suggested that an input/output-based approach must be incorporated into current ISO standards for LCA that are currently based on process-based analysis. Curran and Young [85] and Smith and Peirce [86] felt the need for a genuine methodology for performing LCA. The review of literature indicates that the methodology prescribed by the ISO LCA standards is still unclear [25,85,86].

7.3.4. *Sensitivity and uncertainty analysis*

According to the literature, the current international standards mention conducting a sensitivity and uncertainty analysis but fail to provide an appropriate method for performing them [24,25,84].

7.3.5. *Data availability and quality*

In spite of existing LCA standards emphasizing data quality, issues of reliable, accurate and complete information remain unaddressed [24]. Issues relating to data representativeness, data availability and quality remain top priorities for streamlining the LCA process [24]. Data reliability and incompleteness are two major issues that affect LCA data inventory significantly [87].

8. Recommended approach to embodied energy protocol

Parameters that differ and influence the reported embodied energy values are already identified in this paper and elsewhere [8]. A survey of ISO LCA standards and their critiques indicates that issues, such as system boundary definition and selection, data quality and method of embodied energy measurement, require clarification. A set of guidelines can be developed, which incorporates treatment for differing parameters and clarifications on issues that ISO LCA standards fail to provide (see Fig. 4). These guidelines may be derived by seeking and analyzing scholarly opinion and recommendations on an embodied energy definition and on treatment of differing parameters. Fig. 4 demonstrates a possible approach for developing guidelines that could establish a set of standards.

Most of the identified parameters are either related to data quality or to issues such as system boundary and energy calculation methods. Therefore, guidelines should include, at minimum,

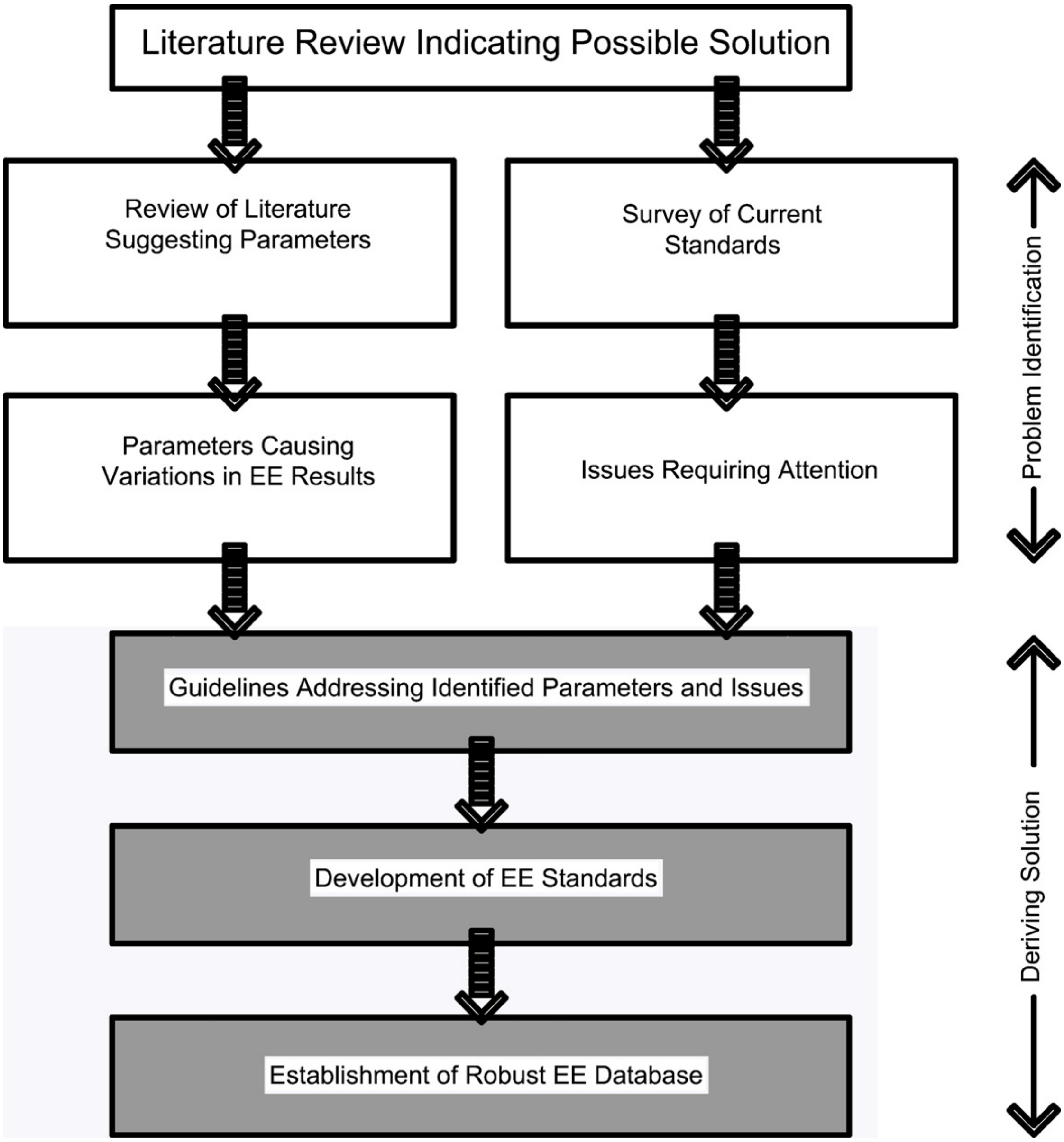

Fig. 4. Proposed approach to establish embodied energy protocol.

embodied energy and other relevant definitions, an embodied energy model for buildings and its components, rules for system boundary selection, a method to measure embodied energy, data quality requirement and data treatment issues (in case of lacking data representativeness). These would provide a foundation for successfully developing and implementing a standard protocol.

This paper anticipates that these guidelines could be further developed and transformed into an embodied energy protocol that could be applied globally. Such a protocol would provide directions on data representativeness issues, such as geography, time and technology. Differences of geography, time and technology may be resolved by deriving a system that translates data belonging to one study into another study of interest (with differing conditions of geography, time and technology). Such a system would help introduce global comparability to current energy data. The embodied energy measurement protocol would address issues relating to inaccuracy and inconsistency of embodied energy data and would help streamline embodied energy analysis as well as the LCA process for a building.

9. Summary

Both the embodied, as well as operational, energy of a building are important. Studies have discussed the growing significance of embodied energy, as a larger number of buildings are becoming energy efficient and energy independent over time. Embodied energy is also a genuine indicator of greenhouse gas emissions, and hence, could be used to assess environmental impacts. However, the current state of research is plagued by a lack of accurate and consistent data and standard methodology.

This paper emphasizes and updates a list of parameters that are responsible for causing data variation and inconsistent results. A review of literature indicates a need to develop an embodied energy protocol that could help streamline the embodied energy analysis process. This calls for a survey of standards that are

currently being used in order to evaluate their performance. In the past, SETAC published LCA guidelines that later provided a foundation for ISO LCA standards. ISO standards for LCA were updated in 2006, and have evolved into two standards, ISO 14040 and ISO 14044. Critical reviews of these standards suggest that they fail to provide complete guidance to LCA studies. Furthermore, critiques point out certain issues that need be resolved in order to simplify and streamline the LCA process.

As suggested by the literature review presented in the manuscript, a possible solution may be to develop a set of guidelines to address differing parameters and unresolved issues. A possible approach, as recommended in this paper, is to develop guidelines for embodied energy measurement that could pave the way to an embodied energy protocol.

10. Future research

A consensus on embodied energy definition and system boundary selection rules could be a potential research work, as it could help create embodied energy calculation guidelines. Furthermore, assessment of parameter impacts identified in this and other published studies on embodied energy data would be vital for embodied energy research.

References

[1] Ding G. The development of a multi-criteria approach for the measurement of sustainable performance for built projects and facilities. Ph.D. Thesis, University of technology, Sydney, Australia; 2004.
[2] Crowther P. Design for disassembly to recover embodied energy. In: The 16th annual conference on passive and low energy architecture. 1999.
[3] Hegner S. Embodied energy for energy efficiency measures, an assessment of embodied energy's relevance for energy saving in the Swiss residential building sector. Diploma Thesis. Department of Environment Science, ETH, Zurich, Switzerland; 2007.
[4] Plank R. The principles of sustainable construction. The IES Journal Part A: Civil and Structural Engineering 2008;1(4):301–7.
[5] Frey P. Building reuse: finding a place on American climate policy agendas. Washington, DC: National Trust for Historic Preservation; 2008.
[6] Nebel B, Alcorn A, Wittstock B. Life cycle assessment: adopting and adapting overseas LCA data and methodologies for building materials in New Zealand. New Zealand: Ministry of Agriculture and Forestry; 2008.
[7] Black C, Ooteghem KV, Boake TM. Carbon neutral steel building systems research project – a case study investigating the relationship of operational energy and embodied energy in achieving a holistic carbon neutral retail building. Phoenix, Arizona, USA: Proceedings of American Solar Energy Society, National Solar Conference; 2010.
[8] Dixit MK, Fernandez-Solis JL, Lavy S, Culp CH. Identification of parameters for embodied energy measurement: a literature review. Energy and Buildings 2010;42(8):1238–47.
[9] Johnston R, Gogstad P, Woolcock J. Benchmarking and Specification of Sustainable Building Products, Envirospec, Sustainability UAE; 2008.
[10] Pears A. Practical and policy issues in analysis of embodied energy and its application. In: Proceeding of the embodied energy: the current state of play seminar. 1996.
[11] Pullen S. Data Quality of embodied energy methods. In: Proceedings of embodied energy seminar: current state of play. 1996.
[12] Raynolds M, Fraser R, Checkel D. The relative mass-energy-economic (RMEE) method for system boundary selection. International Journal of Life Cycle Assessment 2000;5(1):37–46.
[13] Fernandez J. Materials and construction for low-energy buildings in China. In: Glicksman L, Lin J, editors. Sustainable urban housing: principles and case studies for low-energy design in China. Dordrecht, The Netherlands: Springer; 2006.
[14] Atkinson C. Life cycle embodied energy and carbon dioxide emissions in buildings. Industry and Environment 1996;19(2):29–31.
[15] Thormork C. The effect of material choice on the total energy need and recycling potential of a building. Building and Environment 2006;41(8):1019–26.
[16] Davies H. Environmental benchmarking of Hong Kong buildings. Structural Survey 2001;19(1):38–46.
[17] Wan WC. Greening the materials for building and construction: Part 1. The contractor. Official Publication of the Singapore Contractors Association Limited (SCAL); 2008.
[18] Lawson W. LCA and Embodied energy: some contentious issues. In: Proceedings of embodied energy seminar: current state of play. 1996.
[19] Gustavsson L, Joelsson A. Life cycle primary energy analysis of residential buildings. Energy and Buildings 2010;42(2):210–20.
[20] Huberman N, Pearlmutter D. A life-cycle energy analysis of building materials in Negev desert. Energy and Buildings 2008;40(5):837–48.
[21] Ramesh T, Prakash R, Shukla KK. Life cycle energy analysis of buildings, an overview. Energy and Buildings 2010;42(10):1592–600.
[22] Nebel B, Gifford J. Guidelines for LCA practitioners and users of building related LCA studies, TE201/2. Auckland, New Zealand: Beacon Pathway Limited; 2007. p. 1–29.
[23] Khasreen MM, Banfill PFG, Menzies GF. Life cycle assessment and the environment impact of buildings: a review. Sustainability 2009;1(3):674–701.
[24] Reap J, Roman F, Duncan S, Bras B. A survey of unresolved problems in life cycle assessment: Part 2. Impact assessment and interpretation. International Journal of Life Cycle Assessment 2008;13(5):374–88.
[25] Zamagni A, Buttol P, Porta PL, Buonamici R, Masoni P, Guinee L, et al. Critical review of the current research needs and limitations related to ISO-LCA practice. In: Co-ordination Action for innovation in Life-Cycle Analysis for Sustainability project. ENEA, The Italian National Agency on New Technologies, Energy and the Environment; 2008.
[26] Miller AJ. Embodied energy – a life cycle of transportation energy embodied in Construction materials. In: COBRA 2001. 2001.
[27] Upton B, Miner R, Spinney M, Heath L. The greenhouse gas and energy impacts of using wood instead of alternatives in residential construction in the United States. Biomass and Bioenergy 2008;32(1):1–10.
[28] Sartori I, Hestnes AG. Energy use in the life cycle of conventional and low-energy buildings: a review article. Energy and Building 2007;39(3): 249–57.
[29] United States Department of Energy. 2009 buildings energy data book. Washington, DC: United States Department of Energy; 2009.
[30] Optis M, Wild P. Inadequate documentation in published life cycle energy reports on buildings. The International Journal of Life Cycle Assessment 2010;15(7):644–51.
[31] Thormark C. Energy and resources, material choice and recycling potential in low energy buildings. In: CIB Conference, SB 07 Sustainable Construction Materials & Practices. 2007.
[32] Gonzalez MJ, Navarro JG. Assessment of the decrease of CO_2 emissions in the construction field through the selection of materials: practical case studies of three houses of low environmental impact. Building and Environment 2006;41(7):902–9.
[33] Hammond GP, Jones CI. Embodied carbon: the concealed impact of residential construction. Global Warming-Green Energy & Technology 2010:367–84.
[34] John S, Nebel B, Perez N, Buchanan A. Environmental impacts of multi-storey buildings using different construction materials, Research Report: 2008(02), New Zealand Ministry of Agriculture and Forestry, New Zealand, 2008.
[35] Langston YL, Langston CA. Reliability of building embodied energy modeling: an analysis of 30 Melbourne case studies. Construction Management and Economics 2008;26(2):147–60.
[36] Ting SK. Optimization of embodied energy in domestic construction, Master of Engineering Thesis. RMIT, Australia; 2006.
[37] Lenzen M. Errors in conventional and input–output based life cycle inventories. Journal of Industrial Ecology 2000;4(4):127–48.
[38] Pullen S. Energy used in the construction and operation of houses. Architectural Science Review 2000;43(2):87–94.
[39] Langston YL, Langston CA. Building energy and cost performance: an analysis of 30 Melbourne Case Studies. Australian Journal of Construction Economics and Buildings 2007;7(1):1–18.
[40] Sharrard AL. Greening construction processes using an input–output-based hybrid life cycle assessment model. Ph.D. Thesis. Civil and Environmental Engineering, Carnegie Mellon University, Pittsburgh, Pennsylvania, USA; 2010.
[41] Lenzen M, Wood R, Foran B. Direct versus embodied energy: the need for urban lifestyle transitions. In: Droege P, editor. Urban energy transition, from fossil fuel to renewable power. Oxford, UK: Elsevier; 2008.
[42] Hammond G, Jones C. Inventory of Carbon and Energy (ICE), Version 1. 5a Beta, Carbon Vision Buildings Program. UK: University of Bath; 2006.
[43] Crawford RH. Life cycle energy and greenhouse emissions analysis of wind turbines and the effect of size on energy yield. Renewable and Sustainable Energy Reviews 2009;13(9):2653–60.
[44] Adalberth K. Energy use during the life cycle of single-unit dwellings: examples. Building and Environment 1997;32(4):321–9.
[45] Thormark C. A low energy building in a life cycle-Its embodied energy, energy for operation and recycling potential. Building and Environment 2002;37(4):429–35.
[46] Scheuer C, Keoleian GA, Reppe P. Life cycle energy and environmental performance of a new university building: modeling changes and design implications. Energy and Buildings 2003;35(10):1049–64.
[47] Guggemos AA, Horvath A. Comparison of environmental effects of steel-and concrete-framed buildings. Journal of Infrastructure Systems 2005;11(2):93–101.
[48] Norman J, MacLean HL, Kennedy C. Comparing high and low residential density: life-cycle analysis of energy use and greenhouse gas emissions. Journal of Urban Planning & Development 2006;132(1):10–21.
[49] Junnila S, Horvath A, Guggemos AA. Life-cycle assessment of office buildings in Europe and the United States. Journal of Infrastructure Systems 2006;12(1):10–7.
[50] Pearlmutter D, Freidin C, Huberman N. Alternative materials for desert buildings: a comparative life cycle energy analysis. Building Research & Information 2007;35(2):144–55.

[51] Citherlet S, Defaux T. Energy and environmental comparison of three variants of a family house during its whole life span. Building and Environment 2007;42(2):591–8.
[52] Sobotka A, Rolak Z. Multi-attribute analysis for the eco-energetic assessment of the building life cycle, Technological And Economic Development of Economy. Baltic Journal on Sustainability 2009;15(4):593–611.
[53] Verbeeck G, Hens H. Life cycle inventory of buildings: a contribution analysis. Building and Environment 2010;45(4):964–7.
[54] Blengini GA, Dicarlo T. The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings. Energy and Buildings 2010;42(6):869–80.
[55] Buchanan AH, Honey BG. Energy and carbon dioxide implications of building construction. Energy and Buildings 1994;20:205–17.
[56] Crawford RH, Treloar GJ. An assessment of the energy and water embodied in commercial building construction. In: 4th Australian LCA conference. 2005.
[57] Horvath A. Construction materials and the environment. Annual Review of Energy and the Environment 2004;29:181–204.
[58] Joseph P, Tretsiakova-McNally S. Sustainable non-metallic building materials. Sustainability 2010;2:400–27.
[59] Worth D. Embodied energy analysis of buildings: Part 1. Determining the energy contents of building materials. Exedra 1993;4(1):6–13.
[60] Treloar GJ. Extracting embodied energy paths from input–output tables: towards an input–output-based hybrid energy analysis method. Economic Systems Research 1997;9(4):375–91.
[61] Pullen S. Estimating the embodied energy of timber building products. Journal of the Institute of Wood Science 2000;15(3):147–51.
[62] Gelder J. Environmentally responsible specifying – an international survey. ICIS report-3. International Construction Information Society; 1999.
[63] Lenox M, Ehrenfeld JR. Design for environment: a new framework for strategic decision. Total Quality Environmental Management 1995;4(4): 37–51.
[64] Chulsukon P, Haberl J, Sylvester K. Development and analysis of a sustainable low energy house in a hot and humid climate. Ph.D. Thesis. Department of Architecture, Texas A&M University, College Station, Texas, USA; 2002.
[65] Larsson NK. Development of a building performance rating and labeling system in Canada. Building Research and Information 1999;27(4/5):332–41.
[66] Sinou M, Kyvelou S. Present and future of building performance assessment tools. Management of Environmental Quality: An International Journal 2006;17(5):570–86.
[67] Cole RJ. Current levels of performance of green buildings. In: Proceedings: conference on toward 21 century sustainable building and environment. 2000.
[68] Peereboom EC, Kleijn R, Lemkowitz S, Lundie S. The influence of inventory data sets on life cycle assessment results: a case study on PVC. Journal of Industrial Ecology 1998;2(3):109–30.
[69] Lippiatt BC, Norris GA. Selecting environmentally and economically balanced building materials. In: 2nd international green building conference and exposition-1995. 1995. p. 37–46.
[70] Suh S, Lenzen M, Treloar GJ, Hondo H, Horvath A, Huppes G. System boundary selection in Life Cycle inventories using hybrid approaches. Environmental Science and Technology 2004;38(3):657–64.
[71] Insulation Council of Australia and New Zealand (ICANZ). Media Release; 20 February 2006.
[72] Menzies GF, Turan S, Banfill PFG. Life-cycle assessment and embodied energy: a review. Construction Materials 2007;160(4):135–43.
[73] Hammond G, Jones C. Embodied energy and carbon in construction materials. Energy 2008;161(2):87–98.
[74] Weidema BP, Thrane M, Christensen P, Schmidt J, Løkke S. Carbon footprint, a catalyst for Life Cycle Assessment? Journal of Industrial Ecology 2008;12(1):3–6.
[75] Association of Washington Cities. Association of Washington Cities Legislative Bulletin. Energy and Telecommunication 2009;32(February 4).
[76] National Institute of Standards and Technology. Measurement science roadmap for net-zero energy buildings. Workshop summary report. NIST technical note 1660. Gaithersburg, Maryland, USA; 2010.
[77] International Organization for Standardization. ISO 14040 Environmental Management – Life Cycle Assessment – Principles and Framework; 2006.
[78] Ding GKC. Life cycle energy assessment of Australian secondary schools. Building Research & Information 2007;35(5):487–500.
[79] Scientific Applications International Corporation (SAIC), Curran MA. Life Cycle Assessment: Principles and Practice, National Risk Management Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency; 2006.
[80] Fava J. Can ISO life cycle assessment standards provide credibility for LCA? Building Design and Construction 2005;(November):17–20.
[81] International Organization for Standardization. ISO 14044 Environmental Management – Life Cycle Assessment – Requirements and Guidelines. International Organization for Standardization, Geneva, Switzerland; 2006.
[82] Lu H, Masanet E, Price L. Evaluation of life-cycle assessment studies of Chinese cement production: challenges and opportunities. In: The 2009 American council for an energy-efficient economy's summer study on energy-efficiency in industry. 2010.
[83] Heijungs R, Huppes G, Guinee J. A scientific framework for LCA, deliverable (D15) of work package 2(WP2) CALCAS project. Project No. 037075, Co-ordination Action for Innovation in Life Cycle Analysis for Sustainability, CML-Leiden University, Leiden, Netherlands; 2009.
[84] Jeswani HK, Azapagic A, Schepelmann P, Ritthoff M. Options for broadening and deepening the LCA Approaches. Journal of Cleaner Production 2010;18(2):120–7.
[85] Curran MA, Young S. Report from EPA conference on streamlining LCA. International Journal of LCA 1996;1(1):57–60.
[86] Smith JK, Peirce JJ. Life Cycle Assessment Standards: industrial sector and environmental performance. International Journal of LCA 1996;1(2):115–8.
[87] Crawford RH. Validation of a hybrid life-cycle inventory analysis method. Journal of Environmental Management 2008;88(3):496–506.